Constraints on Running Vacuum model

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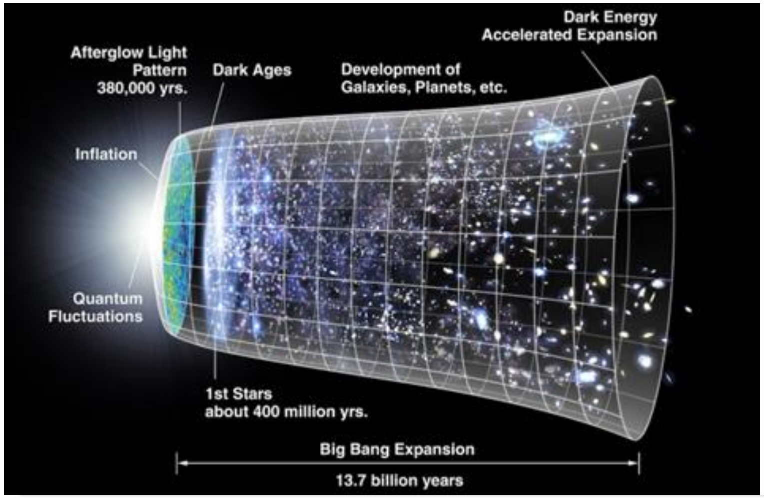
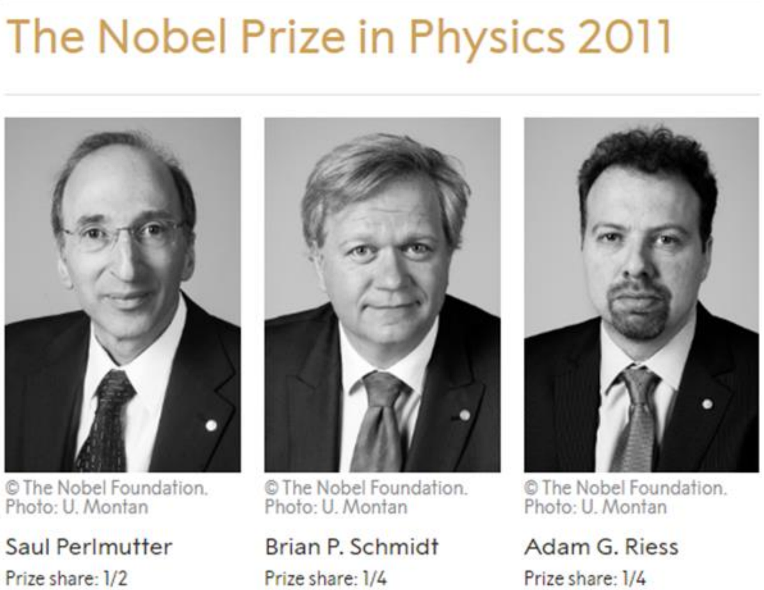
Outline

- The history of ΛCDM and Λ
- Introduce the running vacuum model(RVM)
  (Based on:Chao-Qiang Geng, Chung-Chi Lee and Lu Yin, JCAP 1708, 032 (2017))
- Observational constraints on RVM
- Summary and conclusion

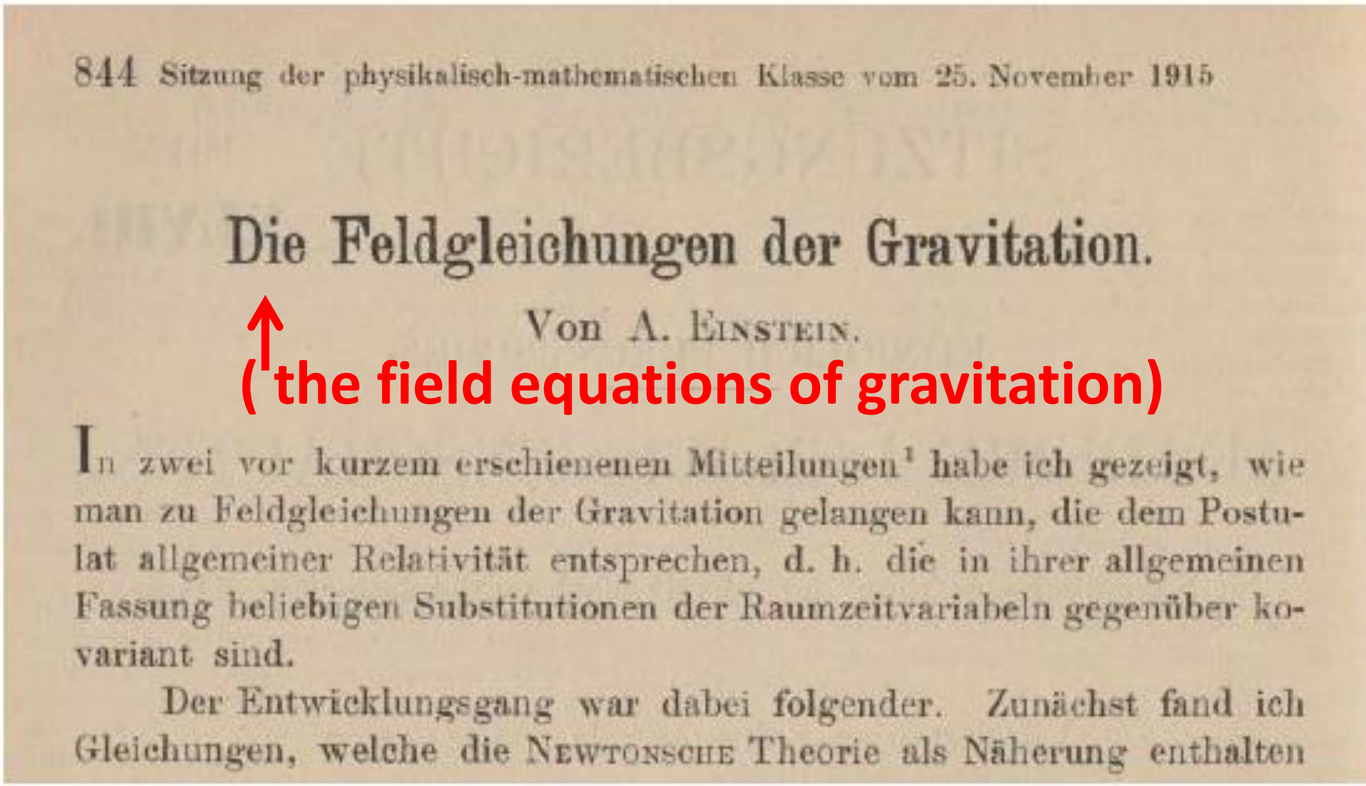
The history of ΛCDM and Λ

- Accelerated expanding universe was found in 1998
- Dark energy is one of a popular solution
- ΛCDM was used to explain this phenomenon





Einstein’s Equations



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

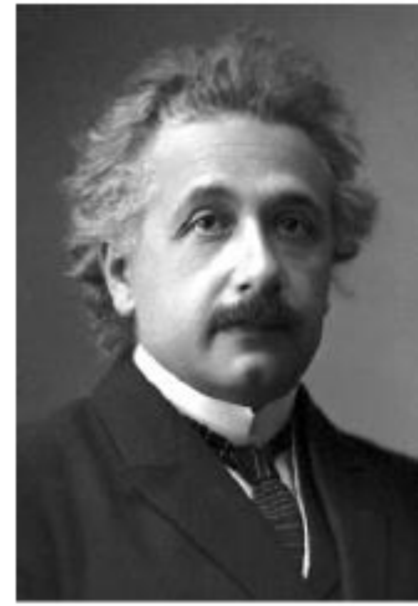
Die Feldgleichungen der Gravitation.

Von A. Einstein.

(the field equations of gravitation)

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten



1915 – 1916

$$\boxed{G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}}$$

This equation can lead to a dynamic universe

Modified Einstein's Equations

1917 Λ appears

A. Einstein, *Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie*, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin, phys.-math. Klasse VI (1917) 142-152.

142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Published in 1917/02/15

(cosmological considerations on the general relativity theory)

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

kommen analog ist. Wir können nämlich auf der linken Seite der Feldgleichung (13) den mit einer vorläufig unbekannten universellen Konstante $-\lambda$ multiplizierten Fundamentaltensor $g_{\mu\nu}$ hinzufügen, ohne daß dadurch die allgemeine Kovarianz zerstört wird; wir setzen an die Stelle der Feldgleichung (13)

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (13a)$$

- The Einstein equation is given by

$$\boxed{R_{\mu\nu} - \frac{g_{\mu\nu}}{2} R + \Lambda g_{\mu\nu} = 8\pi G T^{M}_{\mu\nu}}$$

set $R = g^{\mu\nu} R_{\mu\nu}$ is the Ricci scalar

and $T^{M}_{\mu\nu}$ is the energy-momentum tensor of matter and radiation.

- In 1929, Hubble proposed Hubble's law that the universe is expanding.

- Einstein accepted the idea much later

Lemaitre (in 1927)

Hubble (in 1929)

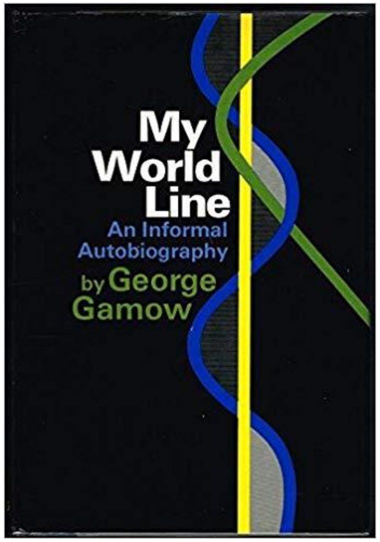
- 1931 Λ disappears ("Einstein's blunder")

A. Einstein, *Zum kosmologischen Problem der allgemeinen Relativitätstheorie,* Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin, phys.-math. Klasse, XII, (1931) 235.

(To the cosmological problem of the general relativity theory)

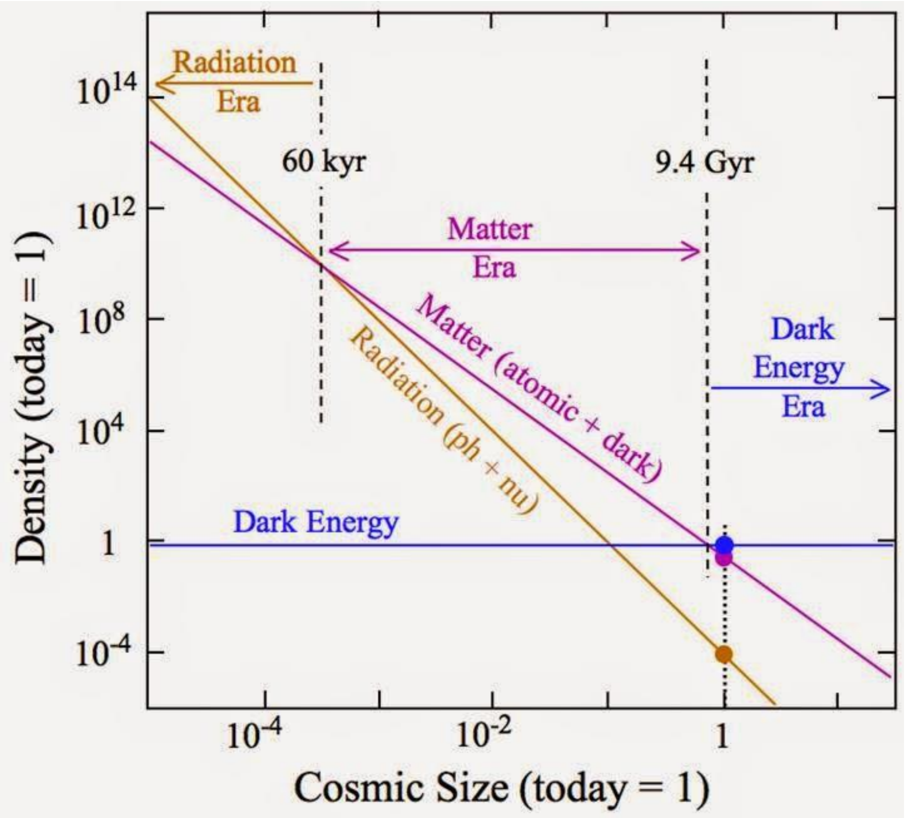
G. Gamow, *My World Line, an Informal Autobiography* (The Viking Press, New York 1970)

- The relevant paragraph (this book P 44) says "Much later, when I was discussing cosmological problem with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life"



➢The problems of Λ:

- coincidence problem
- Nonzero but tiny



➢ One solution to coincidence problem is

$$\rho_\Lambda(H) = \rho_\Lambda^0 + \frac{3\nu}{8\pi} M_P^2 \left(H^2 - H_0^2\right).$$

J. Sola, J. Phys. Conf. Ser. 453 (2013) 012015

Introduce the running vacuum model

To explain the accelerated expansion of the universe, we consider $\Lambda = \Lambda(H)$ is the time-dependent parameter

- Quadratic model:
  - $\Lambda \propto H^2$

    J. C. Carvalho, J. A. S. Lima and I. Waga, Phys. Rev. D **46**, 2404 (1992)
  - $\Lambda = \Lambda_0 + \nu H^2$

    I. L. Shapiro and J. Sola, Phys. Lett. B **475**, 236 (2000)
  - $\Lambda = C_0 + C_{\dot{H}} \dot{H} + C_H H^2$

    S. Basilakos, D. Polarski and J. Sola, Phys. Rev. D **86**, 043010 (2012)
- Linear model: $\Lambda = \sigma H$

  R. Schutzhold, Phys. Rev. Lett. **89**, 081302 (2002)
- Power series models:
  - $\Lambda = n_0 + n_1 H + n_2 H^2$

    S. Basilakos, M. Plionis and J. Sola, Phys. Rev. D **80**, 083511 (2009)

- We consider $\Lambda = \Lambda(H)$ is the time-dependent parameter to explain the accelerated expansion of the universe.

We obtain the Friedmann equations

$$H^2 = \frac{a^2}{3}(\rho_M + \rho_\Lambda)$$

$$\dot{H} = -\frac{a^2}{6}(\rho_M + 3P_M + \rho_\Lambda + 3P_\Lambda)$$

where $H = da/(a\,d\tau)$, τ is the conformal time

$\rho_M = \rho_m + \rho_r$ and $P_M = P_m + P_r = P_r$

The equations of state(EoS) are given by

$$\omega_{r,m,\Lambda} = \frac{P_{r,m,\Lambda}}{\rho_{r,m,\Lambda}} = \frac{1}{3}, 0, -1$$

- We consider Λ to be a function of the Hubble parameter

$$\boxed{\Lambda = 3\nu H^2 + \Lambda_0}$$

where ν and Λ_0 are two free parameters, $\nu \geq 0$

Background evolution of EVM

- From the conservation equation $\nabla^{\mu}(T^{M}_{\mu\nu} + T^{\Lambda}_{\mu\nu}) = 0$

we have

$$\dot{\rho}_{tot} + 3H(1 + \omega)\rho_{tot} = 0$$

$$\dot{\rho}_{\Lambda} + 3H(1 + \omega_{\Lambda})\rho_{\Lambda} = 6\nu H\dot{H} \neq 0$$

resulting in that dark energy unavoidably couples to matter and radiation , given by

$$\dot{\rho}_{m,r} + 3H(1 + \omega_{m,r})\rho_{m,r} = Q_{m,r}$$

↑ Energy transform

Background evolution of RVM

- $Q_{m,r}$ is the decay rate of the dark energy taken to be

$$Q_{m,r} = -\frac{\dot{\rho}_{\Lambda}(\rho_{m,r} + P_{m,r})}{\rho_M} = 3\nu H(1+\omega_{m,r})\rho_{m,r}$$

- Then we get $\rho_{m,r} = \rho_{m,r}^{(0)} a^{-3(1+\omega_{m,r})\xi}$

where $\xi = 1 - \nu$ and $\rho_{m,r}^{(0)}$ are the energy densitys of matter or radiation at $z = 0$.

Perturbation

- The metric perturbations are given by

$$\mathrm{d}s^2 = a^2(\tau)\left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right]$$

$$\mathrm{h}_{ij} = \int d^3k e^{i\vec{k}\cdot\vec{x}}\left[\hat{k}_i \hat{k}_j h(\hat{k},\tau) + 6(\hat{k}_i \hat{k}_j - \frac{1}{3}\delta_{ij})\eta(\hat{k},\tau)\right]$$

i,j=1,2,3 h and η are two scalar perturbations in the synchronous gauge.

- The matter and radiation density perturbations

$$\dot{\delta}_{\mathrm{m},r} = -(1+\omega_{m,r})\left(\theta_{m,r} + \frac{\dot{h}}{2}\right) - 3H\left(\frac{\delta P_{m,r}}{\delta\rho_{m,r}} - \omega_{m,r}\right)\delta_{m,r} - \boxed{\frac{\mathrm{Q}_{m,r}}{\rho_{m,r}}\delta_{m,r}}$$

$$\dot{\theta}_{m,r} = -H(1-3\omega_{m,r})\theta_{m,r} + \frac{\delta P_{m,r}/\delta\rho_{m,r}}{1+\omega_{m,r}}\frac{k^2}{a^2}\delta_{m,r} - \boxed{\frac{\mathrm{Q}_{m,r}}{\rho_{m,r}}\theta_{m,r}}$$

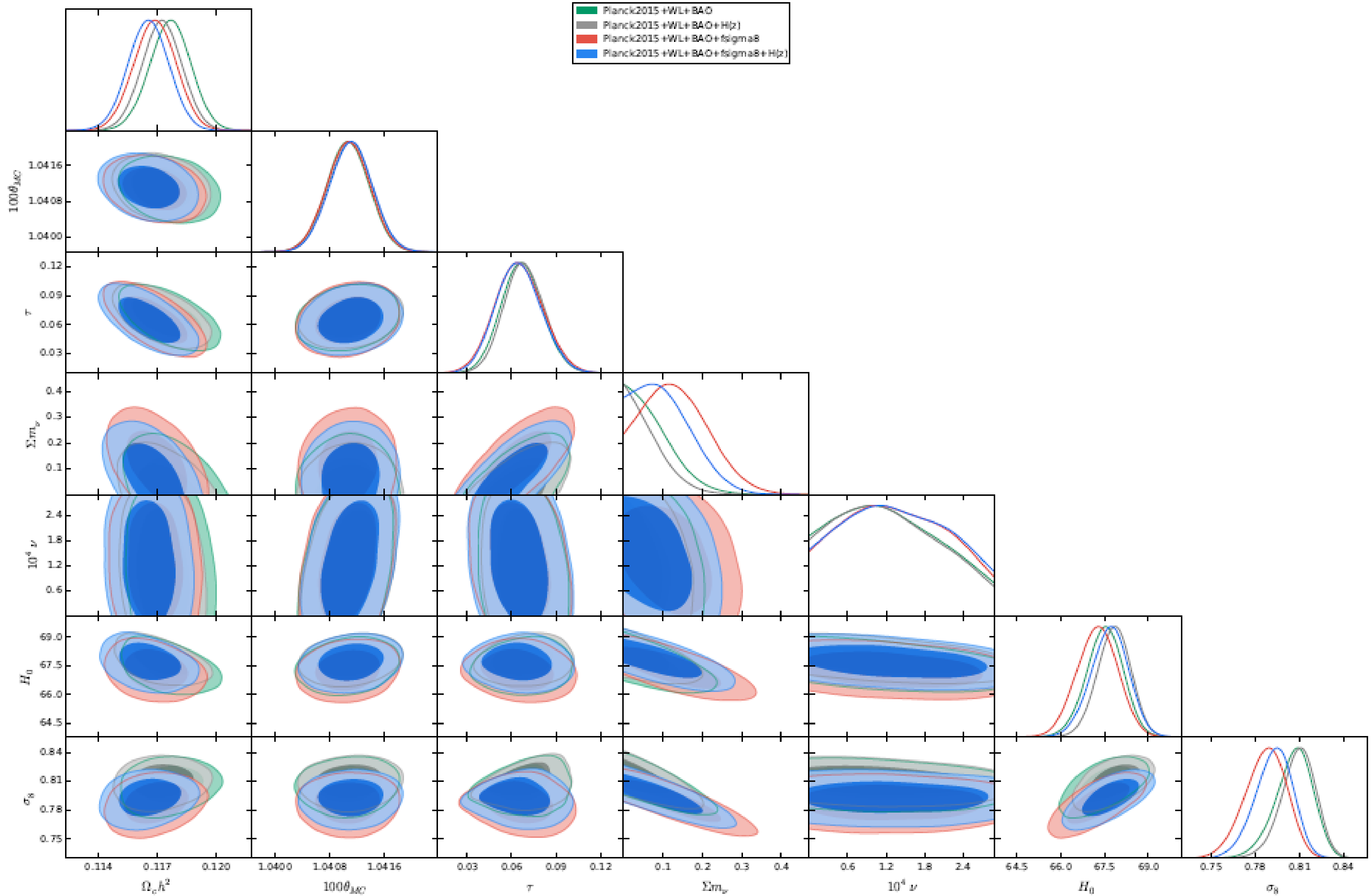
where $\delta_{m,r} \equiv \delta\rho_{m,r}/\rho_{m,r}$ and $\theta_{m,r} = ik_i\upsilon^i_{m,r}$.

Observational constraints on RVM

- We use the **CosmoMC** program to perform the global fitting for the RVM
- Dataset:
  - CMB : Planck 2015

    (TT, TE, EE, lowTEB, low-l polarization and lensing from SMICA)
  - BAO : Baryon acoustic oscillation data from BOSS
  - Weak lensing
  - $H(z)$ data and $f\sigma_8$ data

The result



CQ Geng *et al*., JCAP 1708, 032 (2017)

The result

Fitting results for the RVM with $\Lambda = 3\nu H^2 + \Lambda_0$

Parameter	(A) *Planck* + WL + BAO	(B) *Planck* + WL + BAO + $f\sigma_8$	(C) *Planck* + WL + BAO + $H(z)$	(D) *Planck* + WL+ BAO + $f\sigma_8$ + $H(z)$
Model parameter $10^4\nu$	< 1.83	< 2.09	< 1.80	< 2.09
Baryon density $100\Omega_b h^2$	2.23 ± 0.03 (2.23)	$2.23^{+0.04}_{-0.03}$ (2.24)	$2.23^{+0.02}_{-0.03}$ (2.23)	2.22 ± 0.03 (2.24)
CDM density $100\Omega_c h^2$	11.8 ± 0.2 (11.8)	11.7 ± 0.2 (11.7)	11.7 ± 0.2 (11.7)	$11.7^{+0.2}_{-0.3}$ (11.7)
Optical depth 100τ	$6.67^{+2.83}_{-2.70}$ (6.96)	$6.48^{+3.23}_{-3.03}$ (6.99)	$6.84^{+2.76}_{-2.61}$ (7.13)	$6.49^{+3.08}_{-2.91}$ (6.96)
σ_8	$0.806^{+0.025}_{-0.026}$ (0.810)	$0.787^{+0.027}_{-0.028}$ (0.788)	$0.809^{+0.023}_{-0.024}$ (0.812)	$0.792^{+0.025}_{-0.026}$ (0.793)
Neutrino mass $\Sigma m_\nu/\mathrm{eV}$	< 0.188 (< 0.198)	< 0.278 (< 0.301)	< 0.161(< 0.176)	< 0.235 (< 0.262)
$\chi^2_{best-fit}$	13487.7 (13488.9)	13509.9 (13512.2)	13511.3 (13512.8)	13531.2 (13534.7)

CQ Geng *et al.*, JCAP 1708, 032 (2017)

Summary and conclusion

- The running vacuum model scenario is suitable to describe the late-time accelerating universe at the background level.
- By calculating the pertubation and performing the global fit to the observational data, we have obtained that $\chi^2_{\mathrm{RVM}} < \chi^2_{\Lambda\mathrm{CDM}}$, implying that the current data prefers RVM.

Thank you!